

Effect of manipulated precipitation during the growing season on soil respiration in the desert-grasslands in Inner Mongolia, China

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ARTICLE INFO

Keywords:

Soil carbon flux
Soil carbon
Biomass
Precipitation gradient
Desert-grasslands

ABSTRACT

The dynamics of soil respiration are crucial in understanding carbon cycling and its feedback to climate change. However, little information exists regarding the response of soil respiration to precipitation variation. To examine the response of soil respiration to precipitation variation through biogeochemical regulation, a manipulative field experiment was conducted along a precipitation gradient (−60%, −40%, −20%, CK = natural precipitation, +20%, +40% and +60%) in a native desert grassland ecosystem in Inner Mongolia. Plant biomass, total soil carbon and soil respiration were determined across the precipitation treatments during the growing season (from late May to early October) in 2017. Above-ground biomass tended to increase but total soil carbon varied little with an increase in precipitation. Soil respiration exhibited a unimodal curve diurnally in all precipitation treatments, peaking between 09:00 and 13:00, but showed irregular patterns seasonally. Both the daily and seasonal average soil respirations increased with an increase in precipitation (diurnal R_s ranged from $0.37 \mu\text{mol m}^{-2} \text{s}^{-1}$ to $0.75 \mu\text{mol m}^{-2} \text{s}^{-1}$; seasonal R_s ranged from $0.43 \mu\text{mol m}^{-2} \text{s}^{-1}$ to $0.66 \mu\text{mol m}^{-2} \text{s}^{-1}$). Soil respiration was correlated positively with precipitation-induced change in above-ground plant biomass, but was correlated negatively with precipitation-induced change in total soil carbon. It was concluded that carbon released from the soil increases with an increase in precipitation.

1. Introduction

Soil respiration (R_s) represents CO_2 released from the soil to the atmosphere and plays a key role in regulating the responses of ecosystem and global carbon cycling to natural and anthropogenic perturbations. R_s comprises the second largest terrestrial ecosystem carbon flux, with a range of 68 to 98 Pg C yr^{−1} (Raich and Schlesinger, 1992; IPCC, 2001; Xu and Wan, 2008; Bondlamberty and Thomson, 2010; Zhao et al., 2017). This carbon flux originates from the soil carbon pool, which is the largest carbon reservoir in terrestrial ecosystems (Batjes, 2014), containing at least twice as much carbon as in the atmosphere (Tarnocai et al., 2009).

R_s has been used as an indicator of metabolic activity, persistence

and decomposition of plant biomass input in soil, and the transformation of soil carbon to atmospheric CO_2 (Mukhopadhyay and Maiti, 2014; Guo et al., 2017). Consequently, R_s plays a crucial role in regulating atmospheric CO_2 concentration, climatic dynamics (Luo and Zhou, 2006) and the soil carbon pool in terrestrial ecosystems. The rate of R_s is affected largely by major factors of global climate change such as increased N deposition, elevated CO_2 and precipitation variation (Cardon et al., 2001; Deng et al., 2010; Harper et al., 2005; Zhou et al., 2014). Small changes in soil carbon storage can have considerable effects on the atmospheric CO_2 concentration and produce large feedbacks to the global carbon cycle (Black et al., 2017). Therefore, the pattern of diurnal and seasonal R_s , as well as factors that affect the patterns, are important in understanding the long-term relationship

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<https://doi.org/10.1016/j.catena.2019.01.010>

Received 19 September 2018; Received in revised form 6 December 2018; Accepted 8 January 2019

Available online 15 January 2019

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between soil carbon pool dynamics and climate change (Wang, 2011).

Soil carbon flux has been investigated widely in different vegetations and land uses, including forests (B. Liu et al., 2016), grasslands (Peri et al., 2015; Xu et al., 2015), temperate deserts (Huang et al., 2015), croplands (Jiang et al., 2015; Huang et al., 2016), coastal wetlands (Han et al., 2014), unreclaimed and reclaimed coal mine spoils (Ahrwal and Maiti, 2018a, 2018b), cultivated land converted from forests (Singh et al., 2015), land affected by soil erosion (Wei et al., 2014) and land following fertilizer application (Zhang et al., 2013). These Rs measurements are important in assessing the contribution of carbon emission of different terrestrial ecosystems to the atmospheric CO₂ concentration (Qi et al., 2010). However, assessing the magnitude of Rs at regional and global levels is difficult because of its spatio-temporal variability, consequently, the dynamics of Rs are difficult to evaluate and predict (Zobitz et al., 2008; Bondlamberty and Thomson, 2010).

Variation of Rs was ascribed to changes of biotic (plant community structure, the roots, vegetation cover and microbial community) (Irvine et al., 2008; Xu et al., 2015; Fóti et al., 2016; Du et al., 2018) and abiotic (temperature, moisture and precipitation) factors (Martin and Bolstad, 2005; Concilio et al., 2009). For example, the variation of Rs was associated with changes of plant biomass and mean annual soil water content, both influenced by annual precipitation intensity and frequency (Chen et al., 2010; Cunha et al., 2018). It has been reported that carbon released through Rs is related to carbon pools, including plant biomass, soil organic carbon, and microbial biomass carbon (Phillips and Fahey, 2007; Zhou et al., 2014). However, how the response of these carbon pools to precipitation variation affects Rs needs to be addressed and, consequently, is one of the aims of the present study.

Precipitation variation, both in amount and frequency, is a major component of climate change, which is predicted to increase in mid-latitude regions in the future (IPCC, 2007; Wang, 2011). Decreased precipitation, together with enhanced evaporation in spring and early summer, is very likely to reduce soil moisture in Inner Mongolia (Douville et al., 2002; Wang et al., 2005). Therefore, water-limited ecosystems are likely to be affected by summer droughts in this region. Changes in the amount and distribution of precipitation events affect vegetation cover (van der Molen et al., 2011), ecosystem carbon flux, carbon cycling and carbon storage (Harper et al., 2005). The effects of the spatial variability of soil moisture on Rs are expected to increase (Gerten et al., 2007; Fóti et al., 2016). However, it remains unclear how precipitation variation affects soil carbon flux through altering plant biomass and soil carbon in a desert grassland ecosystem. Arid and semi-arid areas comprise about 30% of the earth's land surface and play a key role in the dynamics of the global terrestrial ecosystem carbon cycle (Li et al., 2017; Poulter et al., 2014). Climate change and climate variability will likely have a substantial impact on arid and semi-arid regions (Jing et al., 2010). Quantifying precipitation effects on Rs will allow us to assess the vulnerability of grassland ecosystems to future climate change.

This study employed a controlled, manipulated precipitation gradient to examine the relationships among precipitation, above and below ground vegetation, total soil carbon and Rs. Measurements of these variables allowed a holistic approach to identify the driving factors of Rs in a fragile desert grassland ecosystem in Inner Mongolia. In this study, we determined (i) the variations of Rs at diurnal and seasonal scales; (ii) the effect of precipitation gradient on Rs; and (iii) on above-ground biomass and total soil carbon.

2. Materials and methods

2.1. Site description

The study was carried out at the Urat Desert-grassland Research Station (106°58'E, 41°25'N, 1650 m a.s.l., Fig. 1), Northwest Institute of

Eco-Environment and Resources, Chinese Academy of Sciences, desert-grasslands in western Inner Mongolia, China. It has a typical temperate continental monsoon climate and is affected by the Mongolian continental high-pressure air mass. The long-term mean annual precipitation (1971–2011) is 140 mm (L.X. Liu et al., 2016), with the rainfall from May to September accounting for about 84% (Fig. S1). The average annual temperature is 6.3 °C, the minimum average annual temperature is 0.72 °C, the maximum average annual temperature is 12.6 °C (2010–2018), and wind speed is up to 5 m/s. The ambient CO₂ concentration at the site during the study was 385 ppm.

The soil types consist mainly of brown and grey brown desert according to the Chinese soil classification system (National Soil Survey Office, 1998). The dominant plant species at the study site were: *Stipa glareosa* P. A. Smirn. (Graminae); *Peganum harmala* L. (Zygophyllaceae); *Asparagus gobicus* Ivan. ex Grubov, *Allium mongolicum* Regel and *Allium polyrhizum* Turcz. ex Regel (Liliaceae); *Reaumuria songarica* (Pall.) Maxim. (Tamaricaceae); *Salsola pellucida* Litv. (Chenopodiaceae) and *Artemisia frigida* Willd. (Compositae). They are all distributed in arid and semi-arid areas across northern China and southern Mongolia. *Stipa glareosa*, with a root depth of < 15 cm (Fig. S2), was the targeted community in the study; therefore, we measured water content in the top 10 cm of soil.

2.2. Experimental design

Precipitation quantities were manipulated with a durable apparatus (National Utility Model Patents, patent number: ZL201220126834.3) described by Zhang et al. (2014), who used the apparatus for long-term monitoring of the impact of rain redistribution on vegetation and soil traits. Receptor grooves, made of organic glass, collected rain into a stainless steel container in front of the receptor. The collected rain was directed from the container to adjacent plots through pipes which had holes to distribute the water evenly (redistributor) (Fig. S3). In this manner, we manipulated precipitation from 60% exclusion to 60% addition, relative to the natural precipitation. All the treatments were applied from May 2015, two years before measurements. A random block design was used in which there were 6 blocks, with each block having 7 precipitation treatments: +60% and –60%, +40% and –40%, +20% and –20% and CK (control). In total, there were 42 plots, each 4 m × 4 m (Fig. S3B). Evapotranspiration is highly variable on the semi-arid Mongolian grasslands and was found to equal precipitation annually (Hao et al., 2015). Furthermore, during the vegetation period, evapotranspiration usually equals or exceeds precipitation (Schaffrath and Bernhofer, 2013). The data from a nearby meteorological station showed that evaporation is 16 times that of precipitation in the growing season (http://data.cma.cn/data/search.html?dataCode=SURF_CLI_CHN_MUL_MM0N_19712000_CES_150). The present study was done during the growing period and, consequently, it is likely that evapotranspiration was much greater than precipitation in all treatment plots.

2.3. Measurements of precipitation, plant biomass and soil properties

Precipitation data were obtained from the weather station at the Urat Desert-grassland Research Station. The natural precipitation was 124 mm during the growing season (from May to September) of 2017. Treatments of –60%, –40%, –20%, +20%, +40% and +60% were established by exclusion or addition of rainfall and their actual manipulated precipitations were 50 mm, 74 mm, 99 mm, 149 mm, 174 mm and 198 mm, respectively. Soil water content (SWC) in the top 10 cm was measured by oven drying soil twice a month from June to September.

Within five selected plots of each treatment, one quadrat (1 m × 1 m) was used to measure biomass and to collect soil samples (in total, 35 quadrats). Above-ground biomass in each quadrat was harvested in late August. Below-ground biomass was measured by

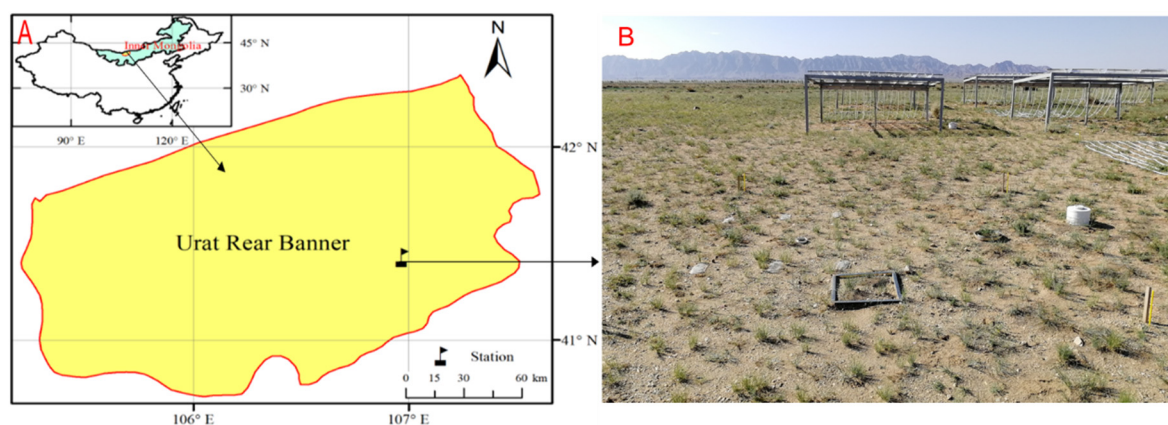


Fig. 1. Location of the study area in Urat Rear Banner of China (A) and long-term study site for manipulated rainfall treatments (B).

sampling three soil cores (8 cm diameter) in each quadrat at a depth of 0–40 cm. The samples were then treated by washing the soil in a mesh bag (mesh size of 0.25 mm). The above- and below-ground biomasses were dried in an oven at 65 °C for 48 h. Top soil samples (0–10 cm) were collected with a soil auger (diameter: 3.0 cm) from each quadrat in late August. After removal of visible roots and debris, soil samples were air-dried at room temperature and put through a 2 mm sieve for measuring soil properties. Soil pH was determined in 1:2.5 soil to water (w/v) ratio with a pH/mV/Cond Meter (SX823, Shanghai San-Xin Instrumentation, China), soil bulk density (SBD) was calculated using the volumetric ring method, and total soil carbon and nitrogen contents were measured by an elemental analyzer (Costech ECS4010, Italy).

2.4. Measurements of soil CO₂ flux

PVC collars (11 cm in diameter, 5 cm long) were installed in the soil of each plot for Rs measurements in April 2017. To eliminate above-ground autotrophic respiration from plants within the collars, we frequently clipped living plants inside the collars and left the clipped plant material on the soil outside the collars (Xu et al., 2015; Du et al., 2018). Thus, Rs measurements excluded surface litter respiration.

All measurements were made during the growing season from late May to early October 2017, 2 years after applying the manipulated precipitation treatments. Rs was measured with a soil respiration chamber (LI-6400-09) on a PVC collar attached to an infrared gas analyzer (IRGA) (LI-6400 Portable Photosynthesis System; Li-Cor, Lincoln, NE, USA). The collar was inserted into the soil to a depth of 3 cm, and stood 2 cm above the ground surface in each plot. Seasonal dynamics of Rs were measured between 9:00 and 12:00 (Beijing time), a time when Rs represented the daily average (Zhang et al., 2015). Measurements were taken twice per month for two cycles each time (90 s for one cycle) from May to October (once in May, August and October), so there were 9 measurements per plot in total. Diurnal variation of Rs was measured at 2–3 h intervals from 6:00–18:00 in early (June), middle (July) and late (September) periods of the growing season, so there were 3 measurements per plot. In total, there were 2016 measurements for the entire study. Soil temperature at a depth of

5 cm was measured continuously in each plot with a thermocouple probe (LI-6400-6000-09TC).

2.5. Statistical analysis

Average seasonal soil CO₂ flux was calculated from the average monthly values. Repeated-measures ANOVA analyses were used to examine the effects of precipitation variation, sampling hour/date and their interactions on Rs. One-way analysis of variance (ANOVA) was used for multi-comparisons of the effect of precipitation on above-ground biomass, total soil carbon, and daily and seasonal average values of Rs, followed by Duncan's post hoc tests. All data are presented as the mean ± standard error. A simple linear model ($y = a + bx$) was used to determine the relationship between Rs and the precipitation-induced change in biomass and in total soil carbon. A level of $P < 0.05$ was accepted as significant. All statistical analyses were done by SPSS 18.0 (SPSS Inc., Chicago, Illinois, USA).

Precipitation variation effects on above-ground biomass, total soil carbon and Rs were defined as: %effect = ((precipitation treatment – control) / control) * 100 (Zhao et al., 2016; Zhang et al., 2017).

3. Results

3.1. Soil properties and soil respiration

3.1.1. Soil properties

Soil pH, soil bulk density, soil inorganic nitrogen and total soil nitrogen did not differ significantly among precipitation treatments (Table S1). Soil water content decreased in all treatments with a decreased precipitation, but did not increase in all treatments with an increased precipitation. Average soil water content from June to September increased with an increase in the precipitation gradient (Table 1).

3.1.2. Diurnal variation and average daily soil respiration

Diurnal variation of Rs was affected significantly by precipitation treatment ($P < 0.001$), sampling hour ($P < 0.001$) and their

Table 1

Soil water content (SWC, %) at the depth of 10 cm from June to September 2017. (Mean ± s.e., n = 5.)

Treatments	–60%	–40%	–20%	CK	+20%	+40%	+60%
June	0.59 ± 0.09c	0.95 ± 0.19bc	1.42 ± 0.13b	2.53 ± 0.16a	2.29 ± 0.26a	2.83 ± 0.31a	2.24 ± 0.20a
July	1.22 ± 0.17e	1.32 ± 0.12de	1.98 ± 0.20cd	2.52 ± 0.25bc	2.93 ± 0.16ab	3.43 ± 0.41a	3.46 ± 0.31a
August	3.35 ± 0.87b	3.79 ± 0.58b	5.52 ± 0.72ab	4.92 ± 0.72ab	4.20 ± 0.58b	5.65 ± 0.61ab	6.68 ± 0.90a
September	1.07 ± 0.26b	2.00 ± 0.21a	1.80 ± 0.10a	2.02 ± 0.18a	2.40 ± 0.36a	2.31 ± 0.07a	2.21 ± 0.12a
Jun. to Sep.	1.48 ± 0.29c	1.94 ± 0.26bc	2.56 ± 0.37ab	2.91 ± 0.28a	2.90 ± 0.23a	3.47 ± 0.31a	3.51 ± 0.42a

Note: Different letters represent significant differences ($P < 0.05$) among treatments. Jun. to Sep. denotes average from June to September.

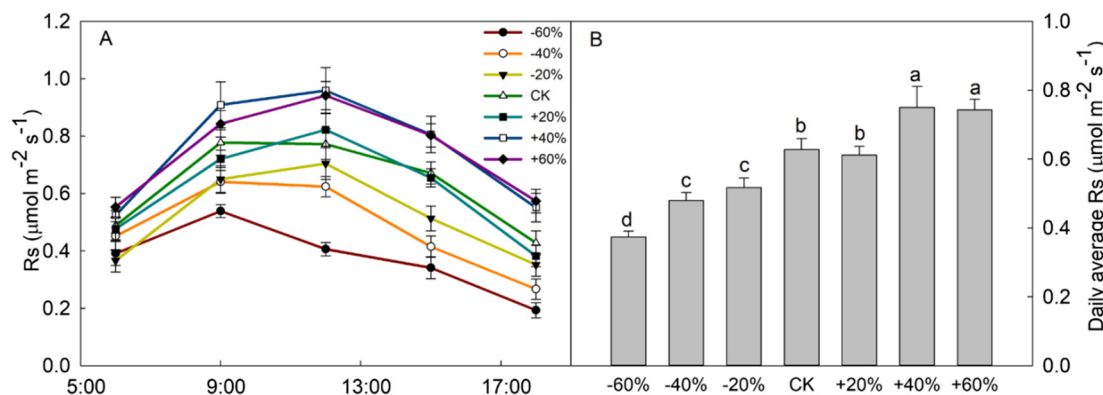


Fig. 2. Diurnal variation of average monthly Rs (A) and average daily Rs (B) in different precipitation treatments in the growing season. Each point represents the monthly mean Rs from June to September. Vertical bars represent standard errors of the mean, $n = 18$. Different letters represent significant differences ($P < 0.05$) among treatments.

interaction ($P = 0.013$; Table S2). Diurnal variation of Rs exhibited a unimodal curve in all precipitation treatments with a peak between 11:00 and 13:00 for the +60%, +40%, +20% and -20% treatments and at 09:00 for the -60%, -40% and CK treatments (Fig. 2A). Daily soil temperature increased and reached a peak between 11:00 and 13:00 (Fig. S4). Rs increased with an increase in soil temperature (Fig. S5).

Average daily Rs increased significantly with increased precipitation, except for the +20% precipitation treatment (Fig. 2B). Average daily Rs increased by 18.3% ($0.74 \mu\text{mol m}^{-2} \text{s}^{-1}$) and 19.4% ($0.75 \mu\text{mol m}^{-2} \text{s}^{-1}$) in the +60%, and +40% precipitation treatments, respectively, and decreased by 2.7% ($0.61 \mu\text{mol m}^{-2} \text{s}^{-1}$), 17.7% ($0.52 \mu\text{mol m}^{-2} \text{s}^{-1}$), 23.6% ($0.48 \mu\text{mol m}^{-2} \text{s}^{-1}$) and 40.4% ($0.37 \mu\text{mol m}^{-2} \text{s}^{-1}$) in the +20%, -20%, -40% and -60% precipitation treatments, respectively, when compared with CK ($0.63 \mu\text{mol m}^{-2} \text{s}^{-1}$).

3.1.3. Seasonal dynamics of soil respiration

Generally, seasonal dynamics of Rs were affected significantly by precipitation treatment ($P < 0.001$) and sampling date ($P < 0.001$), but not by their interaction ($P = 0.159$; Table S3). Rs showed irregular seasonal patterns during the growing season and displayed similar trends among all precipitation treatments (Fig. 3). Both maximum and minimum values of Rs occurred in July.

3.2. Effect of precipitation variation on soil respiration

The average rate of Rs and precipitation-induced changes in Rs were influenced significantly by precipitation variation (Fig. 4). Mean

seasonal Rs increased by 8.8% ($0.63 \mu\text{mol m}^{-2} \text{s}^{-1}$) and 14.4% ($0.66 \mu\text{mol m}^{-2} \text{s}^{-1}$) in the +60% and +40% precipitation treatments, respectively, and decreased by 6.5% ($0.54 \mu\text{mol m}^{-2} \text{s}^{-1}$), 12.7% ($0.50 \mu\text{mol m}^{-2} \text{s}^{-1}$), 12.3% ($0.51 \mu\text{mol m}^{-2} \text{s}^{-1}$) and 26.0% ($0.43 \mu\text{mol m}^{-2} \text{s}^{-1}$) in the +20%, -20%, -40% and -60% precipitation treatments, respectively, when compared with CK ($0.58 \mu\text{mol m}^{-2} \text{s}^{-1}$).

Mean seasonal Rs decreased significantly only in the -60% precipitation treatment compared with CK. However, it did not increase significantly with increased precipitation (Fig. 4A). The effect of precipitation variation on Rs increased in the same proportion between the +60% and +40% precipitation treatments, while it decreased in different proportions in the +20%, -20%, -40% and -60% precipitation treatments (Fig. 4B).

3.3. Plant biomass and total soil carbon and their relationships to soil respiration

3.3.1. Plant biomass and total soil carbon

Above-ground biomass decreased with a decrease in precipitation but was not affected significantly by an increase in precipitation (Fig. 5A). In addition, below-ground biomass (Fig. S6) and total soil carbon (Fig. 5B) were not affected significantly with a change in precipitation. The root weight density ranged from 480 to 765 g m^{-3} among precipitation treatments (Table S4).

3.3.2. Relationship between Rs change and biomass/total soil carbon change

The effect of precipitation variation on biomass increased from

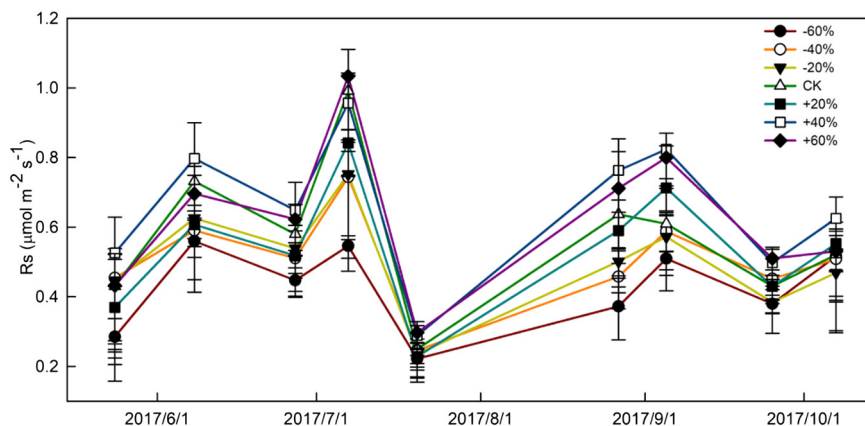


Fig. 3. Seasonal variations of Rs in different precipitation treatments. Vertical bars represent standard errors of the mean, $n = 6$.

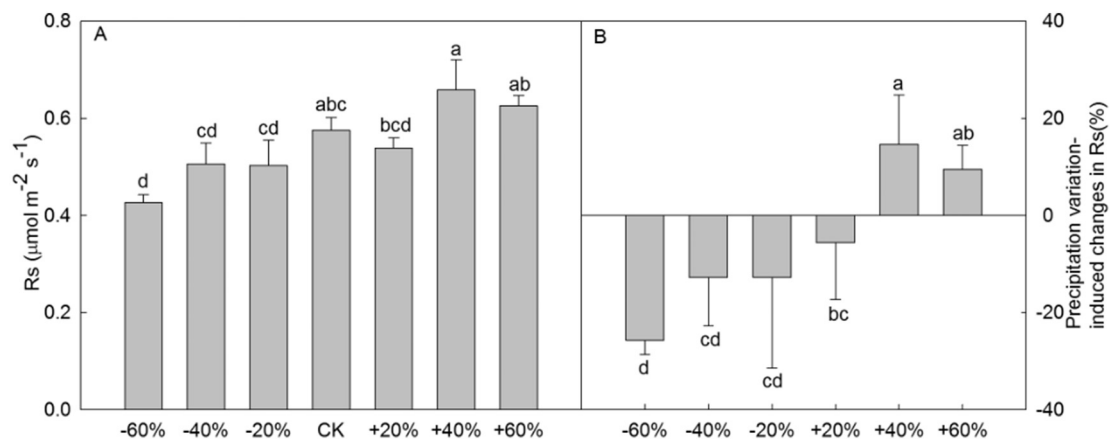


Fig. 4. Average Rs (A) in different precipitation treatments and precipitation-induced changes in Rs (B). Vertical bars represent standard errors of the mean, $n = 54$. Different letters represent significant differences ($P < 0.05$) among treatments.

–64% to 19% with increasing precipitation (Fig. 6A). The effect of precipitation variation on total soil carbon ranged from 11% to 44%, which decreased and then stabilized with increasing precipitation (Fig. 6C). Rs was correlated positively with precipitation-induced changes in biomass (Fig. 6B), but was correlated negatively with total soil carbon (Fig. 6D). Consequently, increased precipitation increased above-ground plant biomass and decreased total soil carbon, which, ultimately, enhanced Rs.

4. Discussion

4.1. Temporal variation characteristics and control factors of soil respiration

In the present study, soil water content did not increase with increased precipitation in June, August and September, which may have resulted due to the following reasons. Firstly, the plant growth period was longer with increased precipitation, and growing plants consumed more soil water. Secondly, lignified plants such as *Heteropappus altaicus* and large numbers of *Corispermum macrocarpum* and *Bassia dasyphylla* appeared in plots with increased precipitation in the middle of the growing season. These plant species are known for their high requirements of soil water (Chen et al., 2007; Fu et al., 2016). Soil water content in all precipitation treatments was highest in August because of high precipitation in July and August. Precipitation variation can alter soil water content (Gherardi and Sala, 2013), which would affect biomass production (Ye et al., 2016) and soil characteristics (Brito et al.,

2009; Sun et al., 2016). Above-ground biomass decreased with a decrease in precipitation, as expected, but was not affected significantly by the increased precipitation. This would suggest that there was an increase in above-ground biomass with an increase in soil water content until a certain level of soil water content was reached and then plateaued. Concomitantly, the below-ground biomass and total soil carbon were not affected significantly, which would suggest that in the allocation of water and nutrients in the vegetation, there was an increase allotted to the above-ground biomass with an increase in precipitation. There was, however, an increase in the below-ground biomass, albeit not significant, at the +40% and +60% treatments.

The diurnal variation of Rs exhibited a unimodal curve in all precipitation treatments with a peak between 09:00 and 13:00, which is in agreement with previous studies in a Hulunber meadow steppe and semi-arid loess plateau of China (Wang et al., 2015; Huang et al., 2016). However, seasonal dynamics of soil CO_2 flux showed irregular patterns in all precipitation treatments, which was also found in steppes of Inner Mongolia, China (Qi et al., 2010). This may have resulted from the unpredictable rainfall events in the water-limited ecosystems in Inner Mongolia. Rs varied with air temperature in the present study. Although air temperatures (see Fig. S8) on June 27 and July 7 were similar, Rs at these dates differed. This resulted from the difference in rainfall before these two dates (see Fig. S7). Consequently, the distribution of rainfall and the variation of air temperature could explain how both maximum and minimum values of Rs occurred in July.

The patterns of seasonal dynamics in Rs in the present study differed from those in alpine meadows on the Tibetan Plateau, where the

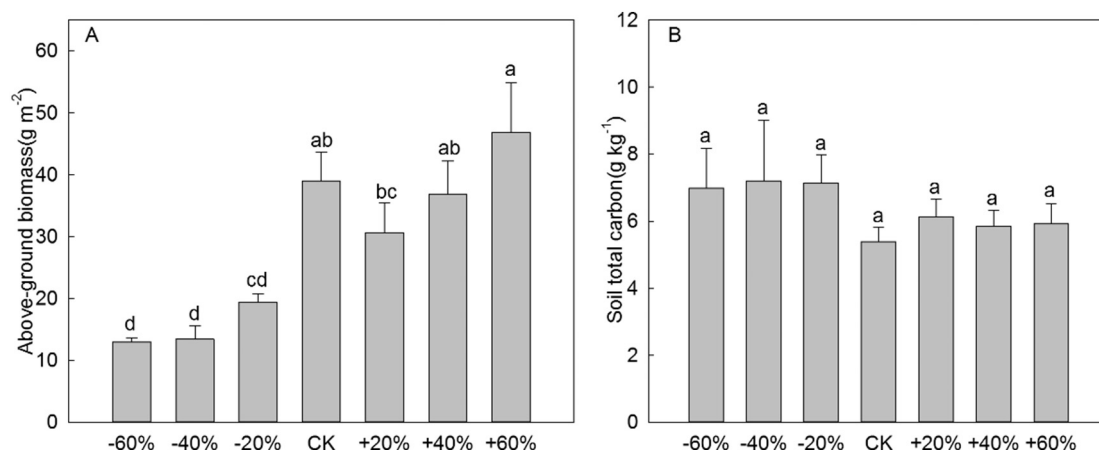


Fig. 5. Above-ground biomass (A) and total soil carbon (B) in different precipitation treatments. Vertical bars represent standard errors of the mean, $n = 5$. Different letters represent significant differences ($P < 0.05$) among treatments.

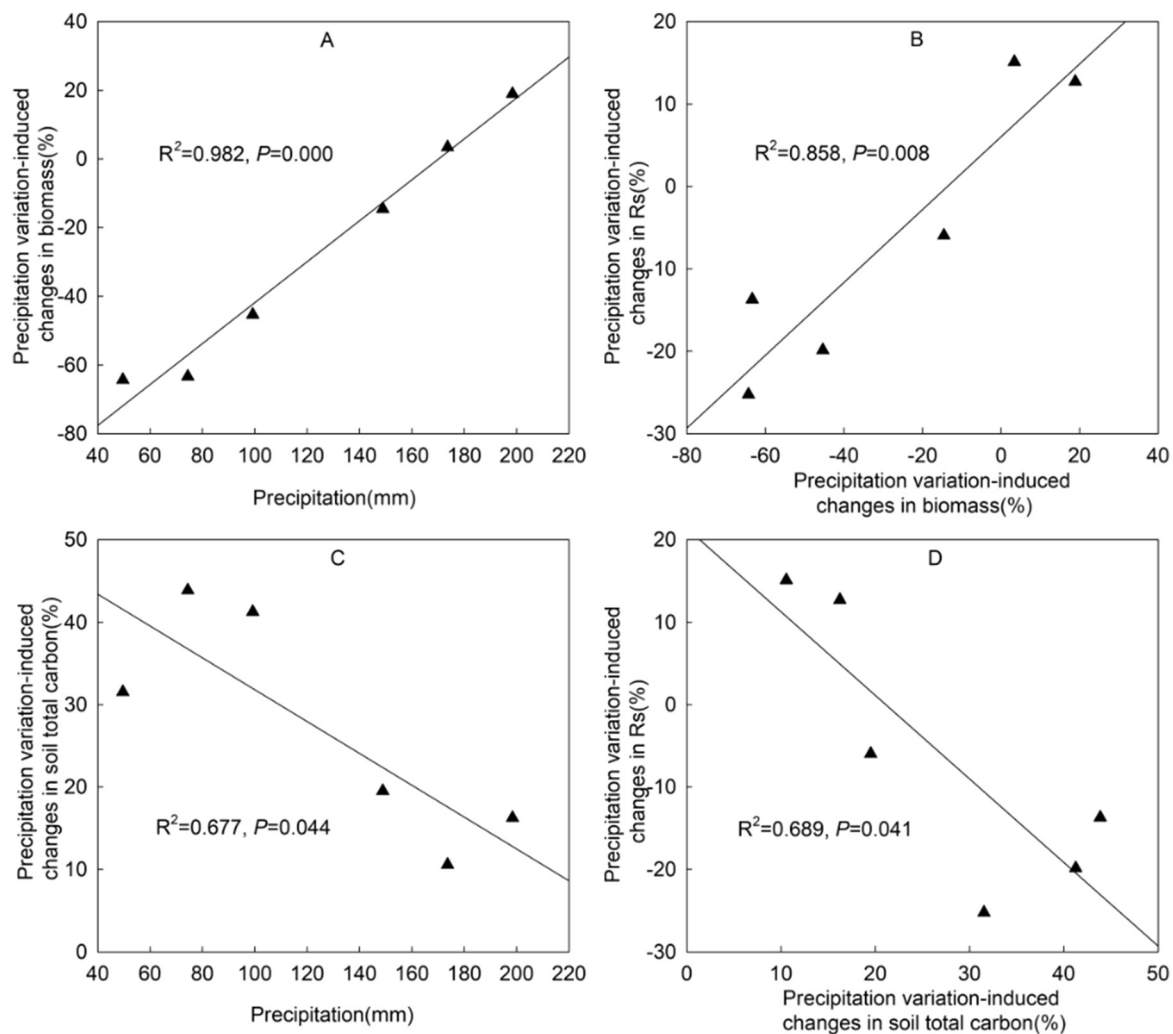


Fig. 6. Relationships of biomass change (A) and total soil carbon change (C) to precipitation. Relationships of Rs change to biomass change (B) and total soil carbon change (D) along the precipitation gradient in the growing season.

unimodal curve peaked in August (Guo et al., 2017). Several factors, including soil moisture, temperature, ecosystem biomass, plant composition, microbial activity, substrate quality, soil use, management, composition of soil organisms and age of reclamation affect Rs (Reichstein et al., 2003; Mukhopadhyay and Maiti, 2014; Song et al., 2017; Cunha et al., 2018). For example, Rs in reclaimed coal mine sites of India was reported to be in the low range, from 0.89 to $2.99 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (Mukhopadhyay and Maiti, 2014; Ahirwal and Maiti, 2018a, 2018b), as a result of poor vegetation cover, low biomass, and low soil water content (Ahirwal and Maiti, 2018a). In general, plant species differ in canopy structure and biomass (Metcalf et al., 2011; Xu et al., 2015), which influences soil physical-chemical characteristics (Aponte et al., 2012) and microbial communities (Huang et al., 2015) and, ultimately, soil carbon flux (Wang, 2011; Du et al., 2018). Precipitation frequency and amount affect Rs by altering plant species and soil microbial composition. Therefore, the difference in seasonal dynamics of Rs between the Urat desert-grassland and alpine meadows on the Tibetan Plateau were most likely due to differences in precipitation amounts and distribution at the two sites.

4.2. Effects of precipitation on soil respiration

In this study, both daily and seasonal average Rs increased with an increase in precipitation. The average daily Rs, calculated from three daytime measurements in the growing season, ranged from

$0.37 \mu\text{mol m}^{-2} \text{ s}^{-1}$ to $0.75 \mu\text{mol m}^{-2} \text{ s}^{-1}$. The mean seasonal Rs ranged from $0.43 \mu\text{mol m}^{-2} \text{ s}^{-1}$ to $0.66 \mu\text{mol m}^{-2} \text{ s}^{-1}$ among precipitation treatments. The range of Rs in the present study was higher than the range of $0.13\text{--}0.49 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in alpine grasslands of Central Asia (Gong et al., 2014), close to the range of $0.51\text{--}0.63 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in the semi-arid northern Great Plains of North America (Liebig et al., 2013) and the average value of $0.56 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in the natural Sal forests of India (Ahirwal et al., 2017), but lower than the range of $0.49\text{--}4.94 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in a subtropical forest plantation of southeast China (Wang, 2011) and the range of $1.10\text{--}1.47 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in an alpine meadow on the Tibetan plateau (Cao et al., 2004; Gong et al., 2014). These substantial differences in Rs among the different ecosystems emphasize that more measurements of the spatio-temporal patterns of soil carbon flux are needed to assess terrestrial ecosystem carbon flux and carbon sequestration potential.

The frequency and intensity of precipitation has been shown to be an important controlling factor of Rs under drought conditions (Borken et al., 1999). The precipitation regime indirectly controlled the inter-annual variation of Rs by affecting soil moisture in subtropical forests (Wang, 2011). Soil water content may affect Rs because water content affects plant and microorganism growth and development (Conant et al., 2004), and plant phenological traits. In the present study, average soil water content from June to September increased with an increase in precipitation, as did Rs. These results indicated that Rs increased with an increase in soil water content in the desert-grassland ecosystem.

The effect of plant phenological traits and growth on Rs should be considered in assessing the ecosystem carbon cycle and carbon sequestration potential (Huang et al., 2016). Some studies suggested that Rs was dependent directly on plant growth (Dornbush and Raich, 2006; Kuzyakov and Gavrichkova, 2010). Precipitation variation alters soil water content (Gherardi and Sala, 2013), which affects plant canopy structure, biomass production (Ye et al., 2016) and soil environment (Brito et al., 2009; Sun et al., 2016) and, ultimately, Rs (Guo et al., 2017). Therefore, precipitation variation has direct and indirect impacts on Rs. Average daily Rs was reduced significantly in the –60%, –40% and –20% precipitation treatments but the average seasonal Rs was reduced significantly only in the –60% treatment. These results suggested that less soil organic matter (SOM) was mineralised and less soil carbon was released with decreased precipitation, which was conducive to carbon sequestration. However, above-ground biomass was reduced significantly with decreased precipitation, which led to low carbon input into the soil, which was not conducive to carbon sequestration. Therefore, precipitation variation affects soil carbon and can lead to both an increase and decrease in ecosystem carbon sequestration under different situations.

The effect of precipitation variation on biomass was enhanced with an increase in precipitation. However, the effect of precipitation variation on total soil carbon decreased with an increase in precipitation. This occurred mainly because soil water content was influenced by precipitation intensity and frequency, and soil water content, in turn, influenced plant growth and other soil properties (Kuzyakov and Gavrichkova, 2010; Wang, 2011). Above-ground plant biomass and Rs showed a consistent trend along the precipitation gradient as Rs was correlated positively with precipitation-induced changes in biomass. These results indicated that above-ground biomass change could serve as an integrated indicator for temporal variations of Rs in desert grasslands. However, Rs was correlated negatively with total soil carbon, which implied that increasing precipitation would enhance above-ground plant biomass and decrease total soil carbon.

5. Conclusion

Both daily and seasonal average Rs values increased with an increase in precipitation. The diurnal pattern of Rs exhibited a unimodal curve in all precipitation treatments in the growing season, peaking between 09:00 and 13:00; however, the seasonal dynamics of Rs showed irregular patterns. Rs was correlated positively with precipitation-induced change in above-ground plant biomass, and was correlated negatively with precipitation-induced change in total soil carbon. The results emphasized that changes in above-ground plant biomass and total soil carbon play an important role in regulating Rs. This is important in understanding the link between above- and below-ground ecosystem carbon processes, which are affected mainly by precipitation. The effects of precipitation gradients on Rs, identified in this study, will facilitate the assessment and simulation of ecosystem carbon sequestration and cycling in desert-grasslands.

Declarations of interest

None.

Acknowledgments

We thank two anonymous reviewers for helpful comments on an earlier draft of the paper. This study was supported financially by the National Basic Investigation Project (2017FY100206), and the National Key Research and Development Plan of China (2016YFC0500506). The authors gratefully acknowledge Li Yaojun for drawing the map of sampling sites and the assistance from the staff and students of the Urat Desert-grassland Research Station and Naiman Desertification Research Station, CAS, for help in the field and laboratory.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.catena.2019.01.010>.

References

- Ahirwal, J., Maiti, S.K., 2018a. Assessment of soil carbon pool, carbon sequestration and soil CO₂ flux in unreclaimed and reclaimed coal mine spoils. *Environ. Earth Sci.* 77 (1), 9.
- Ahirwal, J., Maiti, S.K., 2018b. Development of Technosol properties and recovery of carbon stock after 16 years of revegetation on coal mine degraded lands, India. *Catena* 166, 114–123.
- Ahirwal, J., Maiti, S.K., Singh, A.K., 2017. Changes in ecosystem carbon pool and soil CO₂ flux following post-mine reclamation in dry tropical environment, India. *Sci. Total Environ.* 583, 153–162. <https://doi.org/10.1016/j.scitotenv.2017.01.043>.
- Aponte, C., Garcia, L.V., Maranon, T., 2012. Tree species effect on litter decomposition and nutrient release in Mediterranean oak forests changes over time. *Ecosystems* 15, 1204–1218. <https://doi.org/10.1007/s10021-012-9577-4>.
- Batjes, N.H., 2014. Total carbon and nitrogen in the soils of the world. *Eur. J. Soil Sci.* 65 (1), 2–3.
- Black, C.K., Davis, S.C., Hudiburg, T.W., Bernacchi, C.J., Delucia, E.H., 2017. Elevated CO₂ and temperature increase soil C losses from a soybean-maize ecosystem. *Glob. Chang. Biol.* 23 (1).
- Bondlamberty, B., Thomson, A., 2010. A global database of soil respiration data. *Biogeosci. Discuss.* 7 (6), 1915–1926. <https://doi.org/10.5194/bg-7-1915-2010>.
- Borken, W., Xu, Y.J., Brumme, R., Lamersdorf, N., 1999. A climate change scenario for carbon dioxide and dissolved organic carbon fluxes from a temperate forest soil: drought and rewetting effects. *Soil Sci. Soc. Am. J.* 63, 1848–1855. <https://doi.org/10.2136/sssaj1999.6361848x>.
- Brito, L.D.F., Marques Júnior, J., Pereira, G.T., Souza, Z.M., Scala Júnior, N.L., 2009. Soil CO₂ emission of sugarcane fields as affected by topography. *Sci. Agric.* 66 (1), 77–83. <https://doi.org/10.1590/S0103-90162009000100011>.
- Cao, G.M., Tang, Y.H., Mo, W.H., Wang, Y.A., Li, Y.N., Zhao, X.Q., 2004. Grazing intensity alters soil respiration in an alpine meadow on the Tibetan plateau. *Soil Biol. Biochem.* 36, 237–243.
- Cardon, Z.G., Hungate, B.A., Cambardella, C.A., Chapin, F.S., Field, C.B., Holland, E.A., Mooney, H.A., 2001. Contrasting effects of elevated CO₂ on old and new soil carbon pools. *Soil Biol. Biochem.* 33, 365–373.
- Chen, H., Su, P., Yan, Q., Pu, X., 2007. Preliminary study of plant community characteristics and their relationships with climate in the Hexi corridor region (in Chinese). *Acta Botan. Boreali-Occiden. Sin.* 27 (5), 1008–1016.
- Chen, S., Yao, H., Zou, J., Shen, Q., Hu, Z., Qin, Y., et al., 2010. Modeling interannual variability of global soil respiration from climate and soil properties. *Agric. For. Meteorol.* 150 (4), 590–605.
- Conant, R.T., Dalla-Betta, P., Klopatek, C.C., et al., 2004. Controls on soil respiration in semiarid soils. *Soil Biol. Biochem.* 36 (6), 945–951. <https://doi.org/10.1016/j.soilbio.2004.02.013>.
- Concilio, A., Chen, J., Ma, S., North, M., 2009. Precipitation drives interannual variation in summer soil respiration in a Mediterranean-climate, mixed-conifer forest. *Clim. Chang.* 92 (1–2), 109–122.
- Cunha, J.M.D., Campos, M.C.C., Gaio, D.C., Souza, Z.M.D., Soares, M.D.R., Silva, D.M.P.D., et al., 2018. Spatial variability of soil respiration in archaeological dark earth areas in the amazon. *Catena* 162, 148–156. <https://doi.org/10.1016/j.catena.2017.12.001>.
- Deng, Q., Zhou, G., Liu, J., Liu, S., Duan, H., Zhang, D., 2010. Responses of soil respiration to elevated carbon dioxide and nitrogen addition in young subtropical forest ecosystems in China. *Biogeosciences* 7, 315–328.
- Dornbush, M.E., Raich, J.W., 2006. Soil temperature, not aboveground plant productivity, best predicts intra-annual variations of soil respiration in central Iowa grasslands. *Ecosystems* 9 (6), 909–920. <https://doi.org/10.1007/s10021-005-0093-7>.
- Douville, H., Chauvin, F., Planton, S., Royer, J.-F., Salas-Melia, D., Tyteca, S., 2002. Sensitivity of the hydrological cycle to increasing amounts of greenhouse gases and aerosols. *Clim. Dyn.* 20, 45–68.
- Du, Y., Han, H., Wang, Y., Zhong, M., Hui, D., Niu, S., et al., 2018. Plant functional groups regulate soil respiration responses to nitrogen addition and mowing over a decade. *Funct. Ecol.* <https://doi.org/10.1111/1365-2435.13045>.
- Fóti, S., Balogh, J., Herbst, M., Papp, M., Koncz, P., Bartha, S., et al., 2016. Meta-analysis of field scale spatial variability of grassland soil CO₂ efflux: interaction of biotic and abiotic drivers. *Catena* 143, 78–89. <https://doi.org/10.1016/j.catena.2016.03.034>.
- Fu, B., Wang, S., Liu, Y., Liu, J., Liang, W., Miao, C., 2016. Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess plateau of China. *Annu. Rev. Earth Planet. Sci.* 45 (1), 223–243.
- Gerten, D., Schaphoff, S., Lucht, W., 2007. Potential future changes in water limitations of the terrestrial biosphere. *Clim. Chang.* 80, 277–299. <https://doi.org/10.1007/s10584-006-9104-8>.
- Gherardi, L.A., Sala, O.E., 2013. Automated rainfall manipulation system: a reliable and inexpensive tool for ecologists. *Ecosphere* 4 (2), 18. <https://doi.org/10.1890/ES12-00371.1>.
- Gong, Y.M., Mohammad, A., Liu, X.J., Li, K.H., Christie, P., Fang, F., et al., 2014. Response of carbon dioxide emissions to sheep grazing and N application in an alpine grassland - part 1: effect of sheep grazing. *Biogeosciences* 11 (7), 1751–1757.
- Guo, N., Wang, A., Degen, A.A., Deng, B., Shang, Z., Ding, L., et al., 2017. Grazing exclusion increases soil CO₂ emission during the growing season in alpine meadows on

- the Tibetan Plateau. *Atmos. Environ.* <https://doi.org/10.1016/j.atmosenv.2017.11.053>.
- Han, G.X., Luo, Y.Q., Li, D.J., et al., 2014. Ecosystem photosynthesis regulates soil respiration on a diurnal scale with a short-term time lag in a coastal wetland. *Soil Biol. Biochem.* 68, 85–94. <https://doi.org/10.1016/j.soilbio.2013.09.024>.
- Hao, L., Sun, G., Liu, Y.-Q., Zhou, G.S., Wan, J.H., Zhang, L.B., Niu, J.L., Sang, Y.H., He, J.J., 2015. Evapotranspiration and soil moisture dynamics in a temperate grassland ecosystem in Inner Mongolia, China. *Trans. ASABE* 59 (2), 577–590.
- Harper, C.W., Blair, J.M., Fay, P.A., Knapp, A.K., Carlisle, J.D., 2005. Increased rainfall variability and reduced rainfall amount decreases soil CO₂ flux in a grassland ecosystem. *Glob. Chang. Biol.* 11 (2), 322–334.
- Huang, G., Li, Y., Su, Y.G., 2015. Effects of increasing precipitation on soil microbial community composition and soil respiration in a temperate desert, Northwestern China. *Soil Biol. Biochem.* 83, 52–56.
- Huang, J., Gao, Z., Chen, J., Zhang, H., Xu, B., 2016. Diurnal and seasonal variations of soil respiration rate under different row-spacing in a *Panicum virgatum*, L. field on semi-arid Loess plateau of China. *J. Arid. Land* 8 (3), 341–349.
- IPCC, 2001. Climate change 2001: the science of climate change. In: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, pp. 20.
- IPCC, 2007. IPCC WGI fourth assessment report. In: Climatic Change 2007: The Physical Science Basis. Intergovernmental Panel on Climate Change, Geneva.
- Irvine, J., Law, B.E., Martin, J.G., Vickers, D., 2008. Interannual variation in soil CO₂ efflux and the response of root respiration to climate and canopy gas exchange in mature ponderosa pine. *Glob. Chang. Biol.* 14 (12), 2848–2859. <https://doi.org/10.1111/j.1365-2486.2008.01682.x>.
- Jiang, J.S., Guo, S.L., Zhang, Y.J., et al., 2015. Changes in temperature sensitivity of soil respiration in the phases of a three-year crop rotation system. *Soil Tillage Res.* 150, 139–146. <https://doi.org/10.1016/j.still.2015.02.002>.
- Jing, X., Huang, J., Wang, G., Higuchi, K., Bi, J., Sun, Y., et al., 2010. The effects of clouds and aerosols on net ecosystem CO₂ exchange over semi-arid Loess Plateau of north-west China. *Atmos. Chem. Phys.* 10 (17), 8205–8218.
- Kuzyakov, Y., Gavrichkova, O., 2010. Time lag between photosynthesis and carbon dioxide efflux from soil: a review of mechanisms and controls. *Glob. Chang. Biol.* 16, 3386–3406. <https://doi.org/10.1111/j.1365-2486.2010.02179.x>.
- Li, G.Y., Han, H.Y., Du, Y., Hui, D.F., Xia, J.Y., Niu, S.L., Li, X.N., Wan, S.Q., 2017. Effects of warming and increased precipitation on net ecosystem productivity: a long-term manipulative experiment in a semiarid grassland. *Agric. For. Meteorol.* 232, 359–366.
- Liebig, M.A., Kronberg, S.L., Hendrickson, J.R., Dong, X., Gross, J.R., 2013. Carbon dioxide efflux from long-term grazing management systems in a semiarid region. *Agric. Ecosyst. Environ.* 164 (1), 137–144.
- Liu, B., Mou, C., Yan, G., Xu, L., Jiang, S., Xing, Y., et al., 2016a. Annual soil CO₂ efflux in a cold temperate forest in northeastern China: effects of winter snowpack and artificial nitrogen deposition. *Sci. Rep.* 6 (11), 18957.
- Liu, L.X., Zhao, X.Y., Chang, X.L., Lian, J., 2016b. Impact of precipitation fluctuation on desert-grassland ANPP. *Sustainability* 8 (12), 1245.
- Luo, Y., Zhou, X., 2006. Soil respiration and the environment. In: *Soil Respiration & the Environment*, pp. 257–305.
- Martin, J.G., Bolstad, P.V., 2005. Annual soil respiration in broadleaf forests of northern Wisconsin: influence of moisture and site biological, chemical, and physical characteristics. *Biogeochemistry* 73 (1), 149–182. <https://doi.org/10.1007/s10533-004-5166-8>.
- Metcalfe, D.B., Fisher, R.A., Wardle, D.A., 2011. Plant communities as drivers of soil respiration: pathways, mechanisms, and significance for global change. *Biogeosciences* 8, 2047–2061. <https://doi.org/10.5194/bg-8-2047-2011>.
- Mukhopadhyay, S., Maiti, S., 2014. Soil CO₂ flux in grassland, afforested land and re-claimed coalmine overburden dumps: a case study. *Land Degrad. Dev.* 25, 216–227. <https://doi.org/10.1002/ldr.1161>.
- National Soil Survey Office, 1998. *Soil of China*. China Agriculture Press, Beijing (in Chinese).
- Peri, P.L., Bahamonde, H., Christiansen, R., 2015. Soil respiration in Patagonian semiarid grasslands under contrasting environmental and use conditions. *J. Arid Environ.* 119, 1–8. <https://doi.org/10.1016/j.jaridenv.2015.03.008>.
- Phillips, R.P., Fahey, T.J., 2007. Fertilization effects on fine root biomass, rhizosphere microbes and respiratory fluxes in hardwood forest soils. *New Phytol.* 176, 655–664.
- Poulter, B., Frank, D., Ciais, P., Myneni, R.B., Andela, N., Bi, J., Broquet, G., Canadell, J.G., Chevallier, F., Liu, Y.Y., Running, S.W., Sitch, S., van der Werf, G.R., 2014. Contribution of semiarid ecosystems to inter-annual variability of the global carbon cycle. *Nature* 509, 600–603.
- Qi, Y.C., Dong, Y.S., Liu, L.X., et al., 2010. Spatial-temporal variation in soil respiration and its controlling factors in three steppes of *Stipa* L. in Inner Mongolia, China. *Sci. China Earth Sci.* 53 (5), 683–693.
- Raich, J.W., Schlesinger, W.H., 1992. The global carbon-dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus Ser. B Chem. Phys. Meteorol.* 44, 81–99.
- Reichstein, M., Rey, A., Freibauer, A., Tenhunen, J., Valentini, R., Banza, J., et al., 2003. Modeling temporal and large-scale spatial variability of soil respiration from soil water availability, temperature and vegetation productivity indices. *Glob. Biogeochem. Cycles* 17 (4), 1104–1119.
- Schaffrath, D., Bernhofer, C., 2013. Variability and distribution of spatial evapotranspiration in semi-arid Inner Mongolian grasslands from 2002 to 2011. *Springerplus* 2, 547.
- Singh, M.K., Astley, H., Smith, P., Ghoshal, N., 2015. Soil CO₂-C flux and carbon storage in the dry tropics: impact of land-use change involving bioenergy crop plantation. *Biomass Bioenergy* 83, 123–130.
- Song, X., Kimberley, M.O., Zhou, G., Wang, H., 2017. Soil carbon dynamics in successional and plantation forests in subtropical China. *J. Soils Sediments* 17, 2250–2256.
- Sun, G., Wang, Z., Xia, Z.B., Zhang, N., Wu, N., Liu, L., et al., 2016. Biotic and abiotic controls in determining exceedingly variable responses of ecosystem functions to extreme seasonal precipitation in a Mesophytic alpine grassland. *Agric. For. Meteorol.* 228–229, 180–190. <https://doi.org/10.1016/j.agrformet.2016.07.010>.
- Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G., Zimov, S.A., 2009. Soil organic carbon pools in the northern circumpolar permafrost region. *Glob. Biogeochem. Cycles* 23, GB2023. <https://doi.org/10.1029/2008GB003327>.
- van der Molen, M.K., Dolman, A.J., Ciais, P., Eglin, T., Gobron, N., Law, B.E., Meir, P., Peters, W., Phillips, O.L., Reichstein, M., Chen, T., Dekker, S.C., Doubková, M., Friedl, M.A., Jung, M., van den Hurk, B.J.J.M., de Jeu, R.A.M., Kruijt, B., Ohta, T., Rebel, K.T., Plummer, S., Seneviratne, S.I., Sitch, S., Teuling, A.J., van der Werf, G.R., Wang, G., 2011. Drought and ecosystem carbon cycling. *Agric. For. Meteorol.* 151, 765–773. <https://doi.org/10.1016/j.agrformet.2011.01.018>.
- Wang, Y.D., 2011. Precipitation frequency controls interannual variation of soil respiration by affecting soil moisture in a subtropical forest plantation. *Can. J. For. Res.* 41 (9), 1897–1906.
- Wang, W.J., Zu, Y.G., Wang, H.M., Hirano, T., Takagi, K., Sasa, K., Koike, T., 2005. Effect of collar insertion on soil respiration in a larch forest measured with a LI-6400 soil CO₂ flux system. *J. For. Res.* 10, 57–60. <https://doi.org/10.1007/s10310-004-0102-2>.
- Wang, X., Yan, Y.C., Zhao, S., et al., 2015. Variation of soil respiration and its environmental factors in Hulunber meadow steppe (in Chinese). *Acta Ecol. Sin.* 35 (1), 1–4.
- Wei, S., Zhang, X., McLaughlin, N.B., Liang, A., Jia, S., Chen, X., et al., 2014. Effect of soil temperature and soil moisture on CO₂ flux from eroded landscape positions on black soil in northeast China. *Soil Tillage Res.* 144 (4), 119–125.
- Xu, W., Wan, S., 2008. Water- and plant-mediated responses of soil respiration to topography, fire, and nitrogen fertilization in a semiarid grassland in northern China. *Soil Biol. Biochem.* 40 (3), 679–687.
- Xu, X., Shi, Z., Li, D., Zhou, X., Sherry, R.A., Luo, Y., 2015. Plant community structure regulates responses of prairie soil respiration to decadal experimental warming. *Glob. Chang. Biol.* 21, 3846–3853. <https://doi.org/10.1111/gcb.12940>.
- Ye, J.S., Reynolds, J.F., Maestre, F.T., Li, F.M., 2016. Hydrological and ecological responses of ecosystems to extreme precipitation regimes: a test of empirical-based hypotheses with an ecosystem model. *Perspect. Plant Ecol. Evol. Syst.* 22, 36–46.
- Zhang, X.B., Xu, M.G., Sun, N., Wang, X.J., Wu, L., Wang, B.R., et al., 2013. How do environmental factors and different fertilizer strategies affect soil CO₂ emission and carbon sequestration in the upland soils of southern China? *Appl. Soil Ecol.* 72 (2), 109–118.
- Zhang, L.M., Liu, X.P., Zhao, X.Y., Zhang, T.H., Yue, X.F., Yun, J.Y., 2014. Response of sandy vegetation characteristics to precipitation change in Horqin Sandy Land (in Chinese). *Acta Ecol. Sin.* 34 (10), 2737–2745.
- Zhang, T., Wang, G., Yang, Y., Mao, T., Chen, X., 2015. Non-growing season soil CO₂ flux and its contribution to annual soil CO₂ emissions in two typical grasslands in the permafrost region of the Qinghai-Tibet Plateau. *Eur. J. Soil Biol.* 71, 45–52.
- Zhang, T., Wang, G., Yang, Y., Mao, T., Chen, X., 2017. Grassland types and season-dependent response of ecosystem respiration to experimental warming in a permafrost region in the Tibetan plateau. *Agric. For. Meteorol.* 247, 271–279.
- Zhao, J., Luo, T., Li, R., Li, X., Tian, L., 2016. Grazing effect on growing season ecosystem respiration and its temperature sensitivity in alpine grasslands along a large altitudinal gradient on the central Tibetan Plateau. *Agric. For. Meteorol.* 218–219, 114–121.
- Zhao, J., Li, R., Li, X., Tian, L., 2017. Environmental controls on soil respiration in alpine meadow along a large altitudinal gradient on the central Tibetan Plateau. *Catena* 159, 84–92.
- Zhou, L., Zhou, X., Zhang, B., Lu, M., Luo, Y., Liu, L., et al., 2014. Different responses of soil respiration and its components to nitrogen addition among biomes: a meta-analysis. *Glob. Chang. Biol.* 20 (7), 2332.
- Zobitz, J.M., Moore, D.J.P., Sacks, W.J., Monson, R.K., Bowling, D.R., Schimel, D.S., 2008. Integration of process-based soil respiration models with whole-ecosystem CO₂ measurements. *Ecosystems* 11 (2), 250–269.